

# Planned & Future Missions

## Human Exploration of the Solar System by 2100

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*"Pathways Beyond Low Earth Orbit"*  
In-Space Chemical Propulsion TIM  
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# INTRODUCTION



- **Human Exploration of the Solar System by 2100 as a Strategic National Goal**
  - Vision to Revitalize HSF in Service to Security, Economic, & Scientific Interests of Nation
  - Requires Multi-Decade Commitment Employing Radically Advanced Technologies
  - Enormous Costs will Demand Public, Private, & International Collaboration
- **HSF Timeline & Mission Drivers**
  - Inner Solar System (through 2050) – Near-Earth, Cis-Lunar & Mars
    - Achievable via Chemical Propulsion, Split-Chemical/SEP, Hybrid-Chemical/SEP or NTP/NEP
    - Facilitate Econo-Space Development & Commercial Opportunities
    - Establish Outposts, Permanent Bases & Colonies
  - Outer Solar System (2050 to 2100) – Beyond Mars
    - Requires Highly Energetic Processes/Concepts beyond NTP
    - Harsh Space Radiation Environment & Sustained Zero Gravity Impose Strict Biological Constraints
    - Enable In situ Human Exploration
- **HSF Mission Case Studies**
  - Examine Mission Scenarios to Define Quantifiable Propulsion Capability Needs
    - Duration constrained roundtrip missions
  - Evaluate Advanced Propulsion Technology Landscape
    - Identify advanced propulsion architectures capable of fulfilling mission need
- **Diversified Capability Development Strategy**
  - 2030-2050 Inner Solar System Missions
  - 2050-2100 Outer Solar System Missions





# SOLAR SYSTEM CARTOGRAPH

## *The Big Picture*

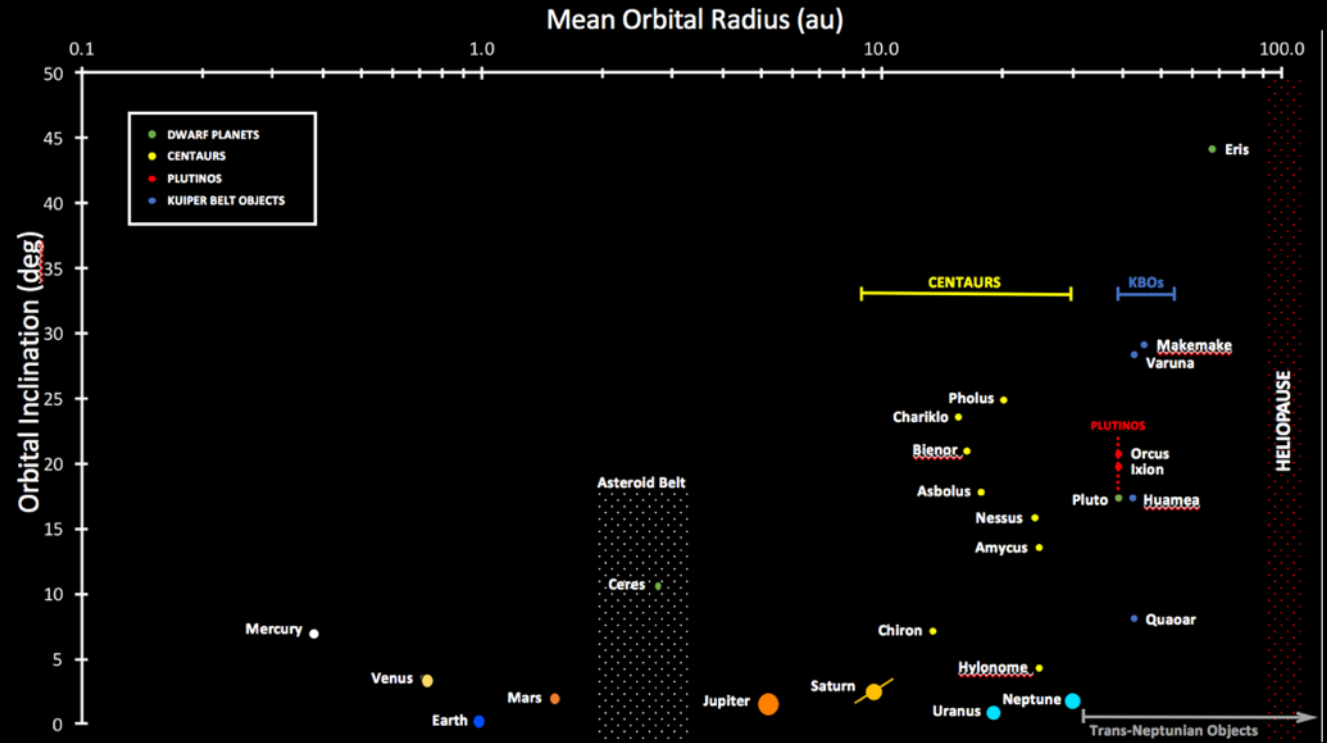


### Destination Types

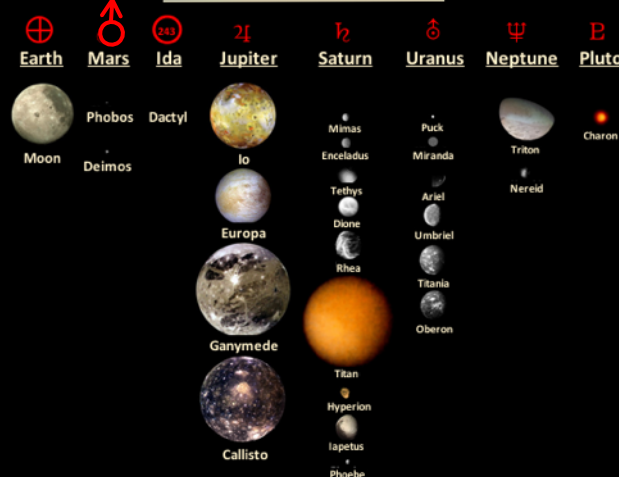
- Primitive Bodies
  - Asteroids & Comets
  - Dwarf Planets & Centaurs
  - Trans-Neptunian Objects
  - Plutinos & KBOs
- Inner Planetary Systems
  - Mercury to Mars
  - Moons
- Outer Giants & Icy Planets
  - Jupiter to Neptune
- Moons of Giants & Icy Planets
  - Large Satellites

### Exploration Sequence Modes

- Flyby Reconnaissance
  - Free Trajectory S/C
- Rendezvous Encounters
  - Orbiters, Probes, Landers
- Robotic In Situ Exploration
  - Roving Labs & SR
- Human In Situ Exploration
  - Habitats & Mobility



### NOTABLE MOONS



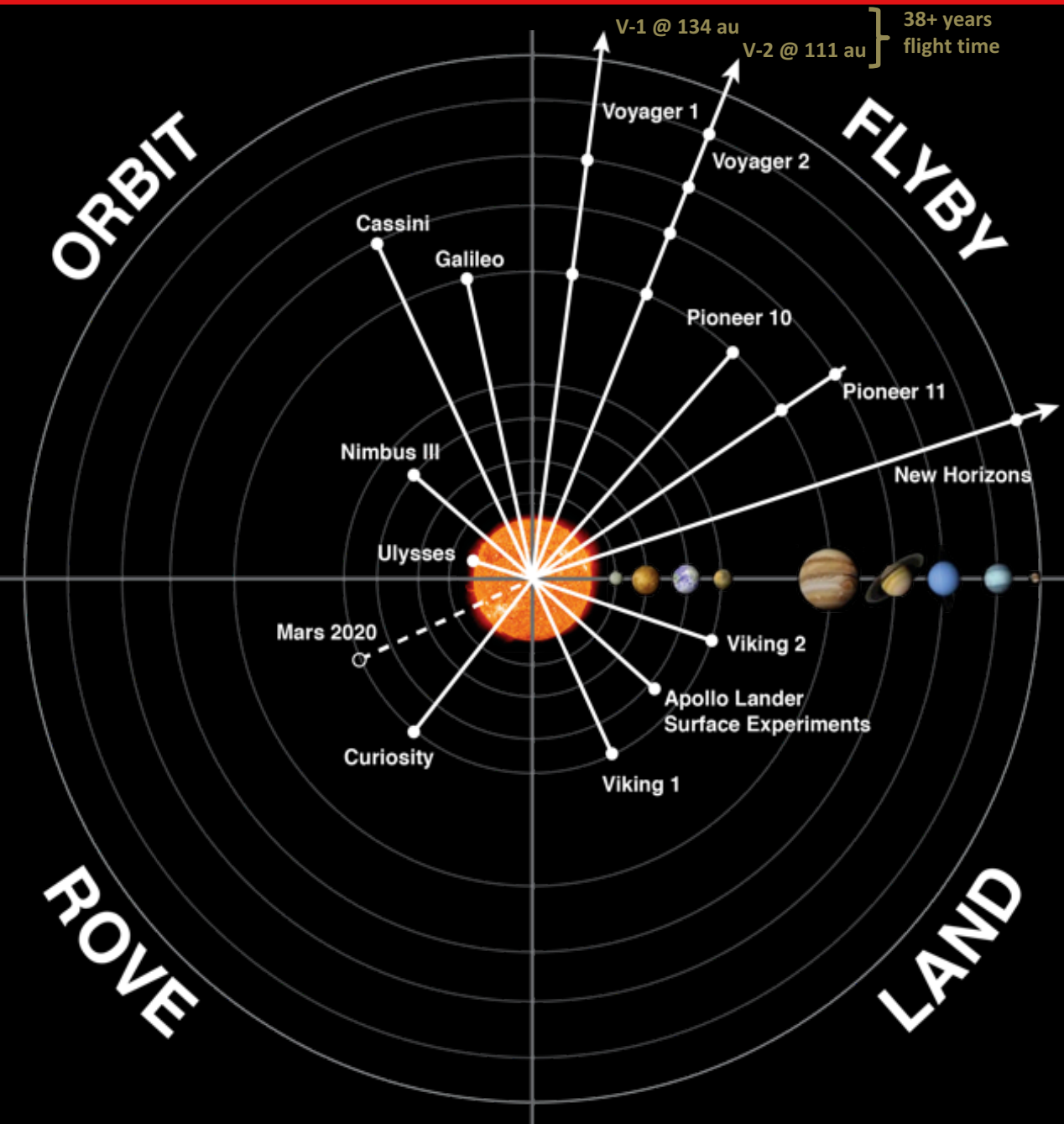
### TRANS-NEPTUNIAN OBJECTS



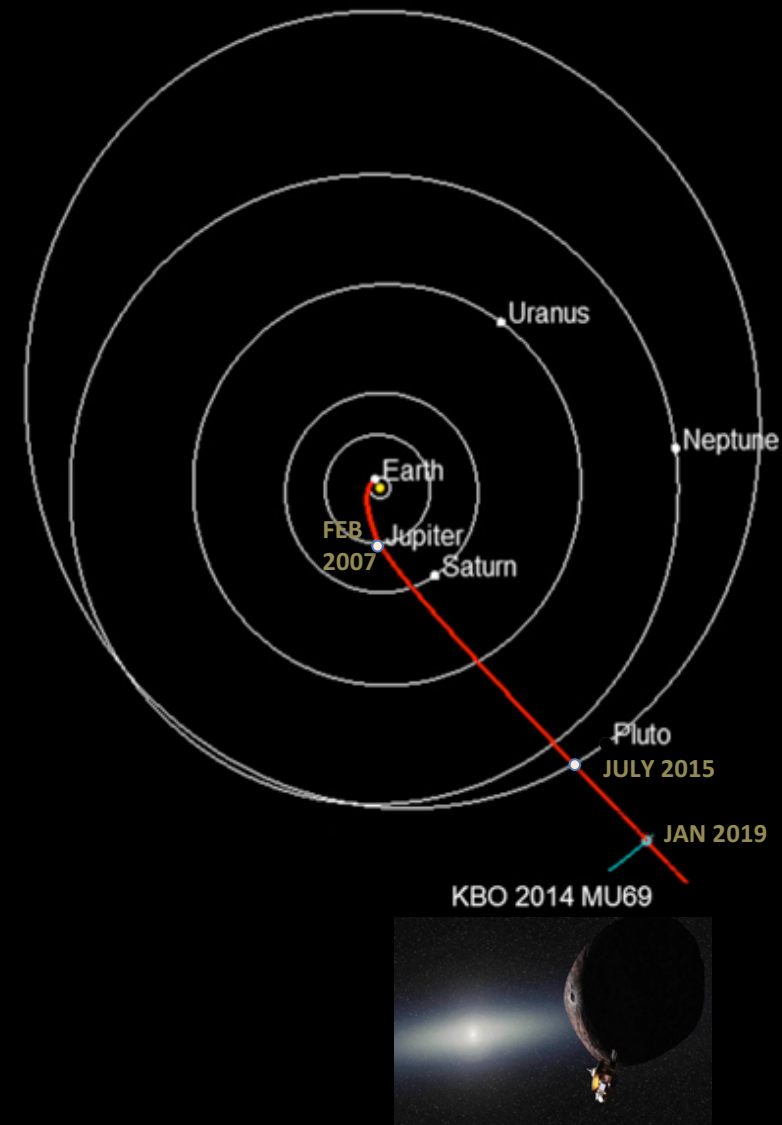


# KEY DEEP SPACE MISSION MILESTONES

*Notable Robotic & Human Spacecraft Heritage*



## NEW HORIZONS MISSION





# SPACE RADIATION ENVIRONMENT

## Radiation Sources & Biological Effects

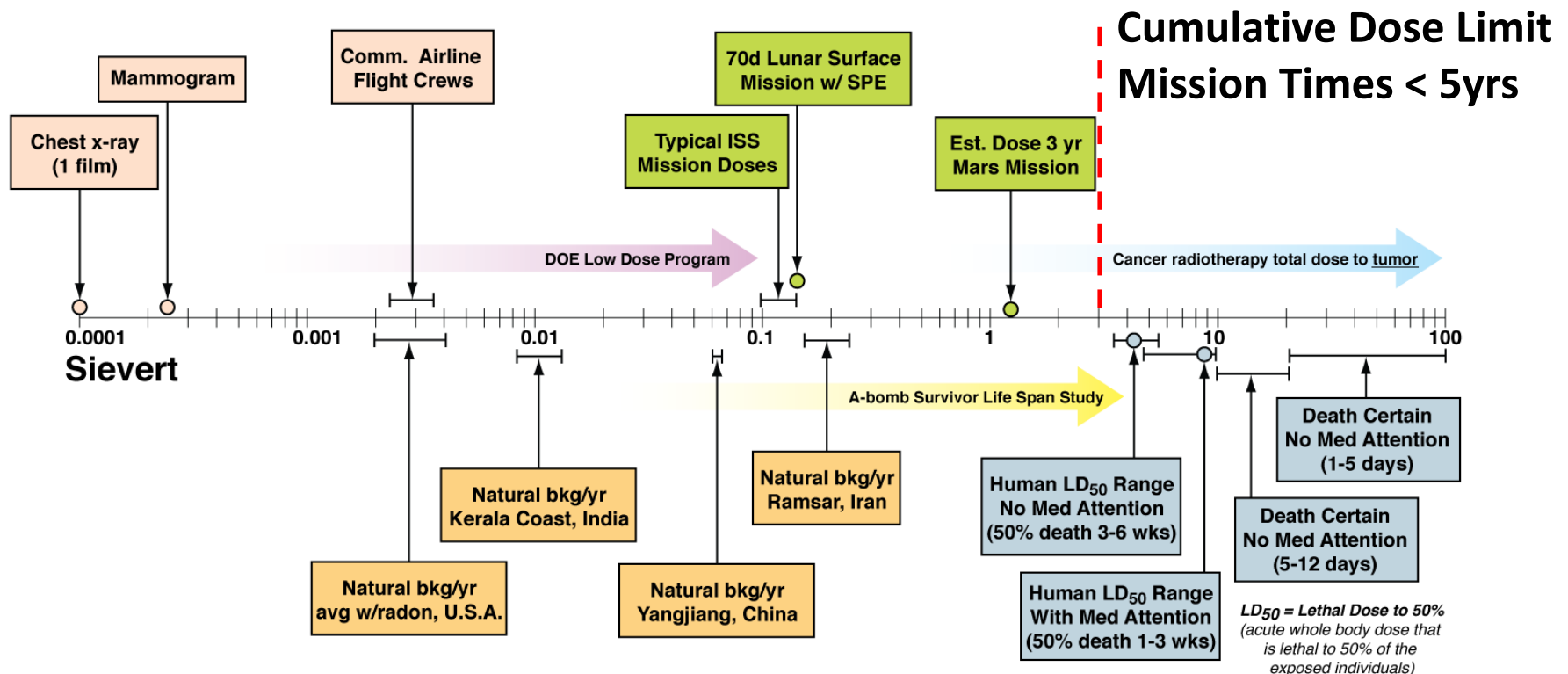


- **Space Radiation Sources**

- Solar Energetic Particles (SEP)
  - Intermittent proton showers from Solar Flares/CMEs
  - Potentially lethal but limited peak energy permits effective shielding solutions – PRACTICAL
- Galactic Cosmic Radiation (GCR)
  - Near continuous flux of high-energy heavy ions
  - Protective shielding requires an effective depth equivalent to Earth's atmosphere – IMPRACTICAL

- **Mission Driving Biological Effects (1 Sievert = 100 REM)**

- Annual Allowable Dose for Middle Age Astronaut = 0.4 Sv
- Lifetime Limit Depends on Astronaut Gender & Age = 1.5 – 3.0 Sv





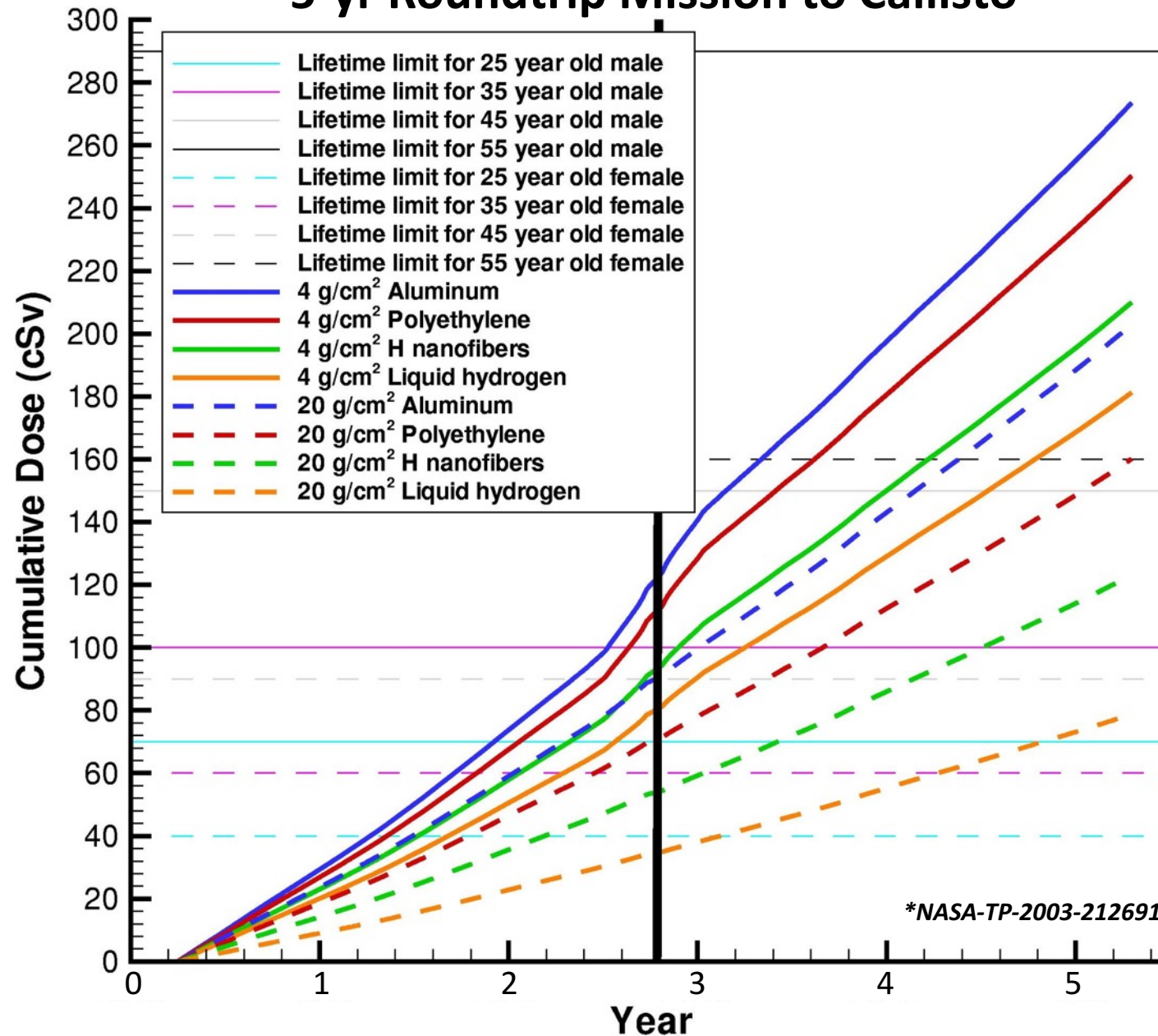


# HSF RADIATION CONSTRAINTS

## 5-Year Mission Cumulative Dose



### 5-yr Roundtrip Mission to Callisto\*

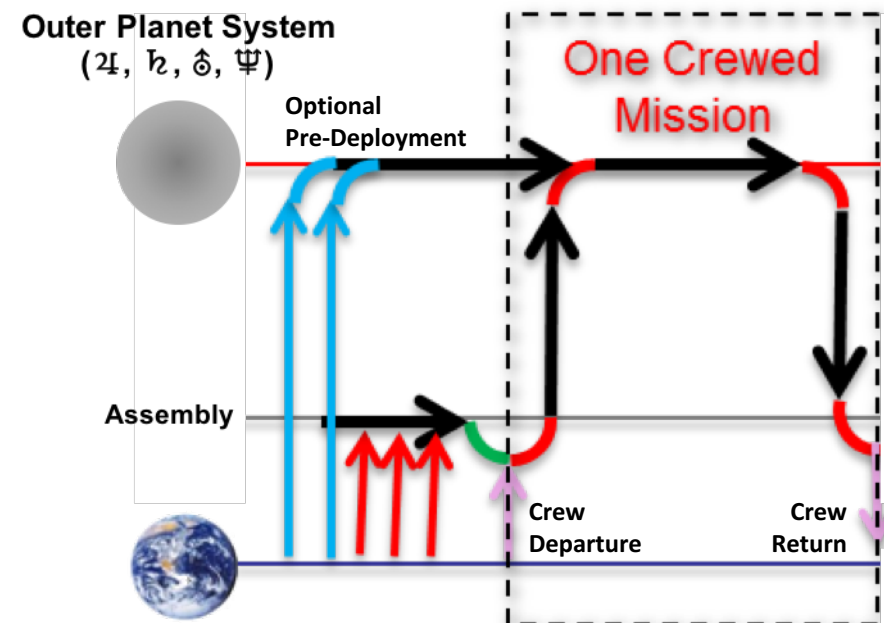
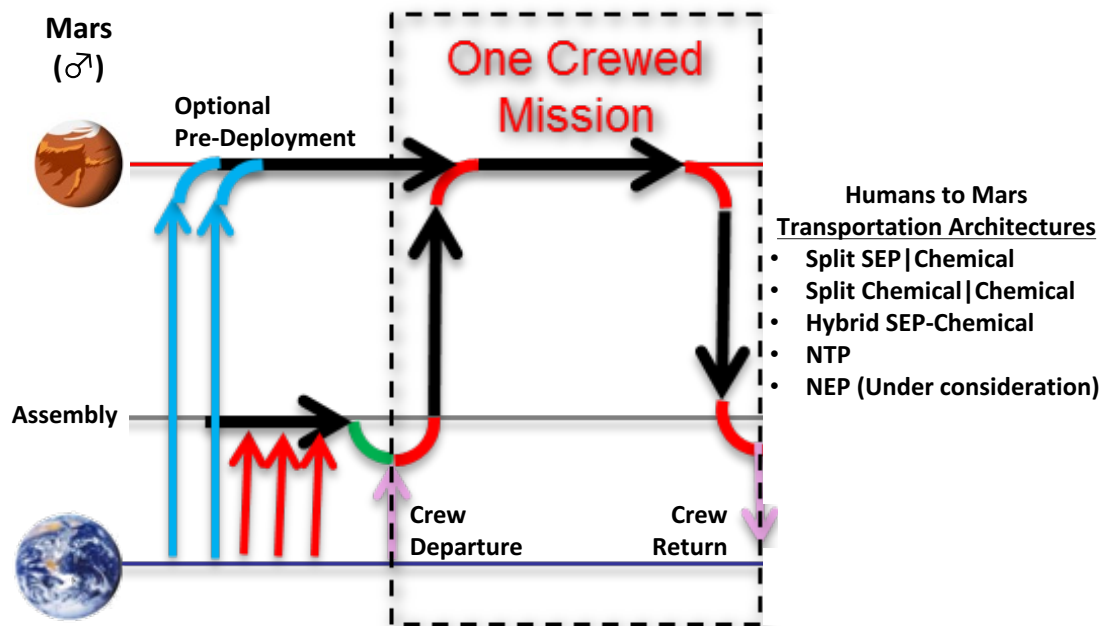


# HSF MISSION CASE STUDIES

## Assumptions & Analysis Approach



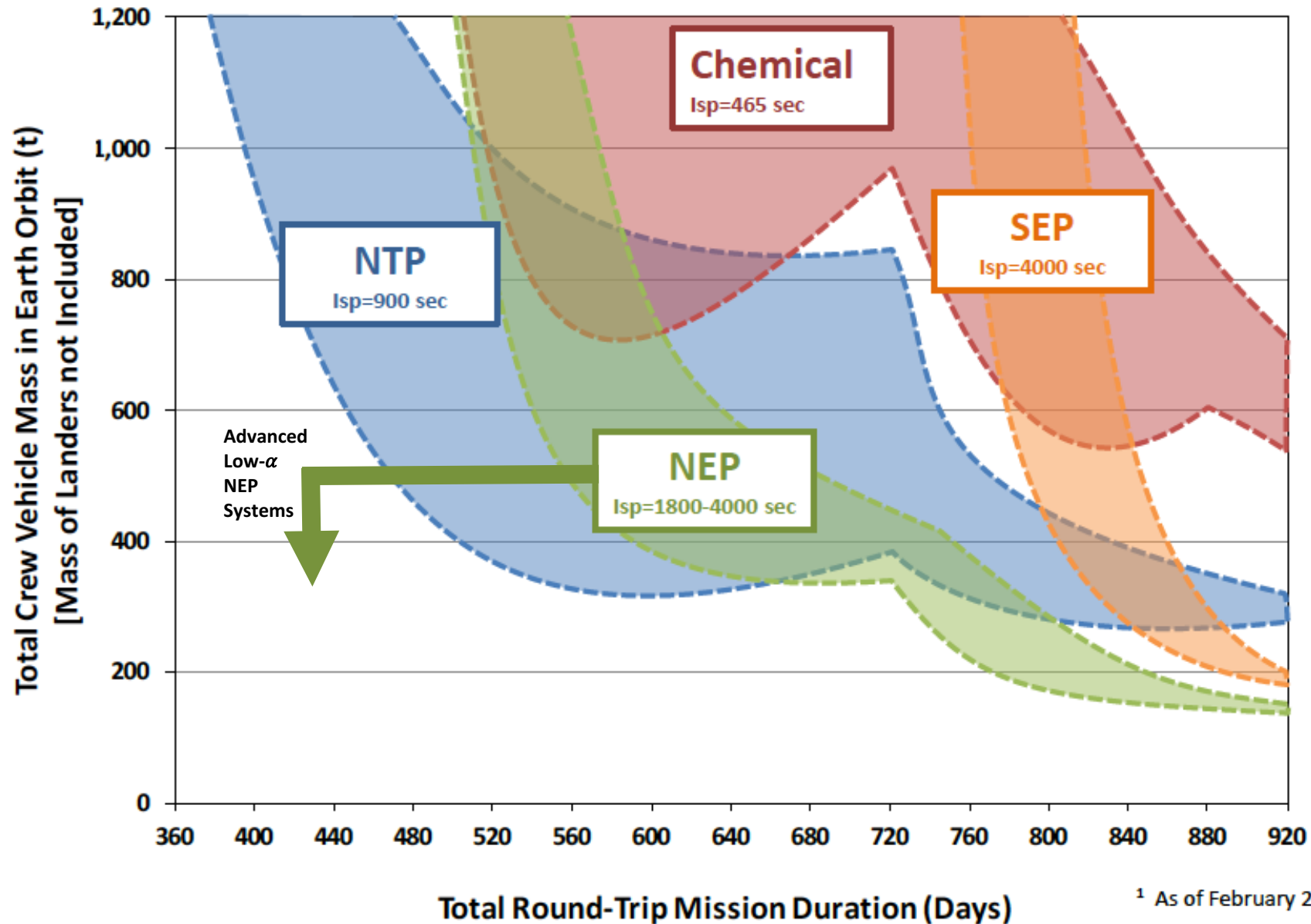
- **Inner Solar System – Mars**
  - NASA Design Reference Architecture 5.0
- **Outer Solar System – Jupiter/Saturn/Uranus/Neptune Systems**
  - 4-yr Roundtrip Flight Time
  - 2-yr Flyout Time
  - Thrust-to-Coast Ratio = 1.0 to 1.3
  - $C_3 = 0$  (km<sup>2</sup>/s<sup>2</sup>) at Mission Departure
  - 20% Flyout Payload Mass Fraction
    - Includes habitat, structures, propulsion system, & flyback propellant
    - Baseline analysis assumes no pre-deployments
  - Propulsion System Treated Parametrically
    - Jupiter/Saturn:  $P = 100$  MW &  $\eta_t = 80\%$
    - Uranus/Neptune:  $P = 200$  MW &  $\eta_t = 80\%$





# DRA-5 MARS MISSION SCENARIOS

## *Propulsion System Architecture Trades*



<sup>1</sup> As of February 2013

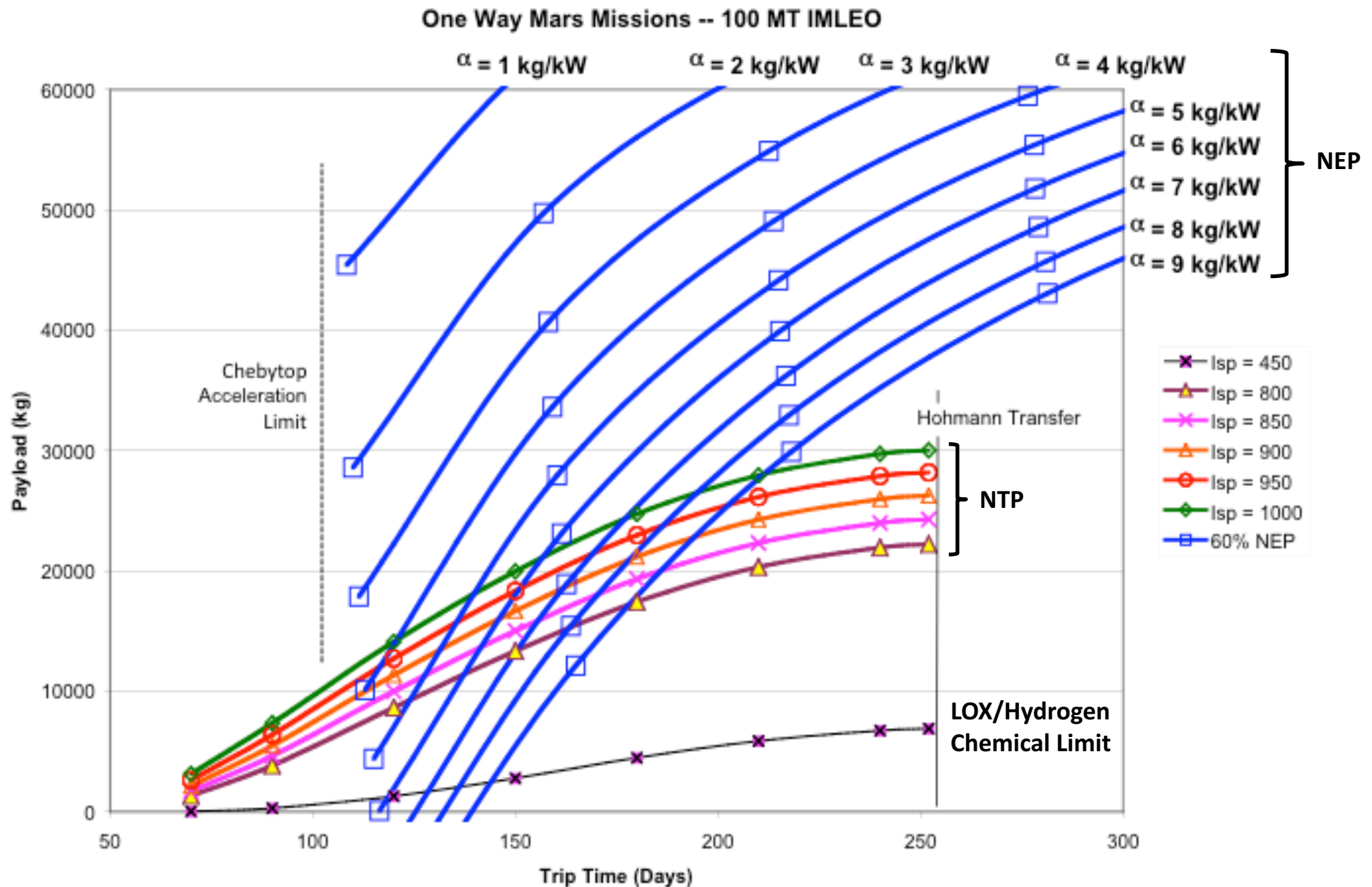
**NOTE: DRA-5 Assumes Near-Term NEP Propulsion System Specific Mass  $\approx$  25 kg/kW**





# PILOTED MARS MISSION SCENARIOS

## Propulsion System Sensitivities



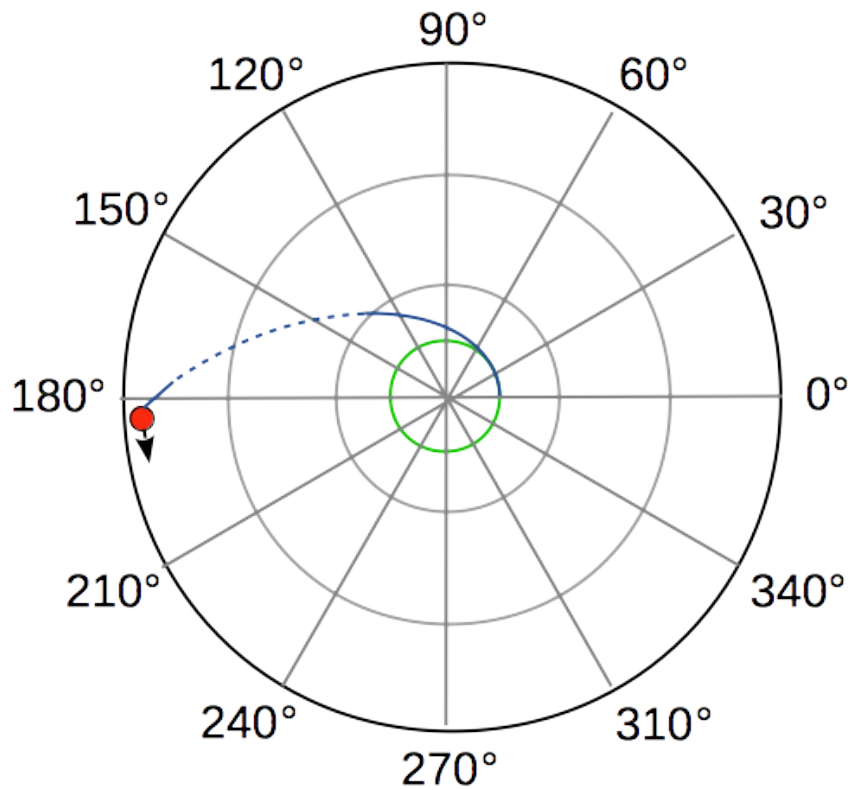


# OUTER PLANET MISSION CASE STUDIES

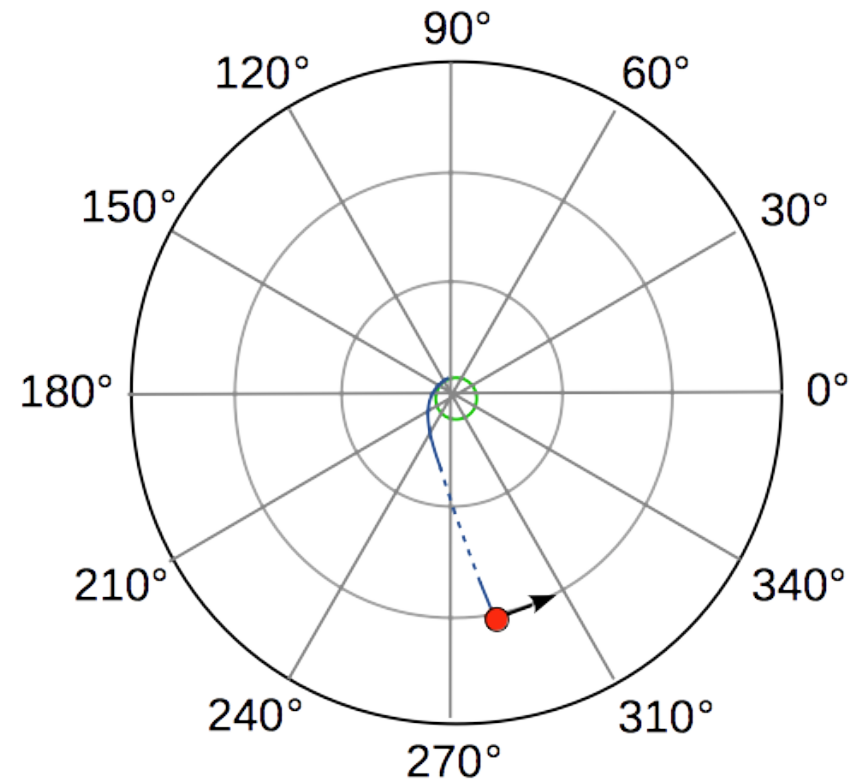
## *Flyout Trajectories & Velocity Profiles*



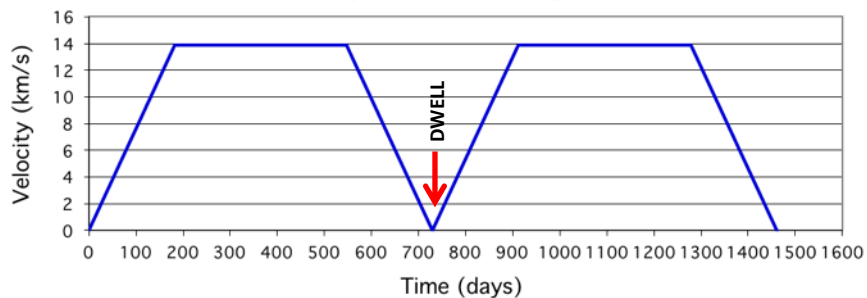
### Jupiter Flyout Trajectory



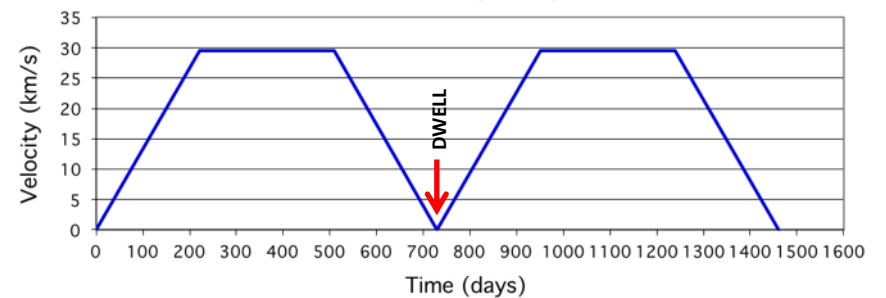
### Saturn Flyout Trajectory



### Jupiter Round Trip Velocity Profile



### Saturn Round Trip Velocity Profile



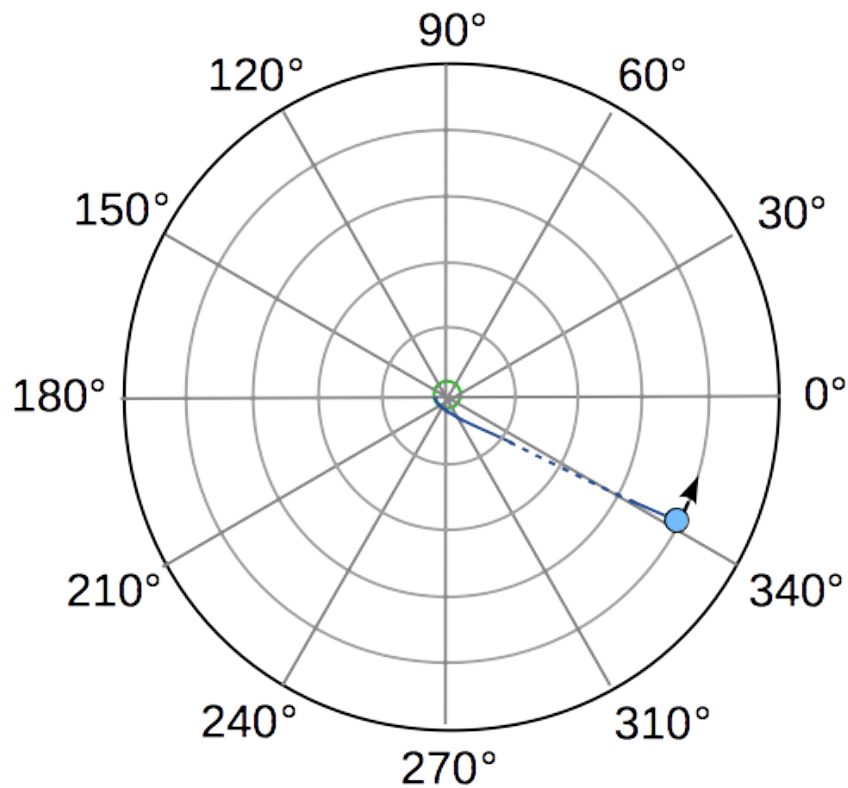


# OUTER PLANET MISSION CASE STUDIES

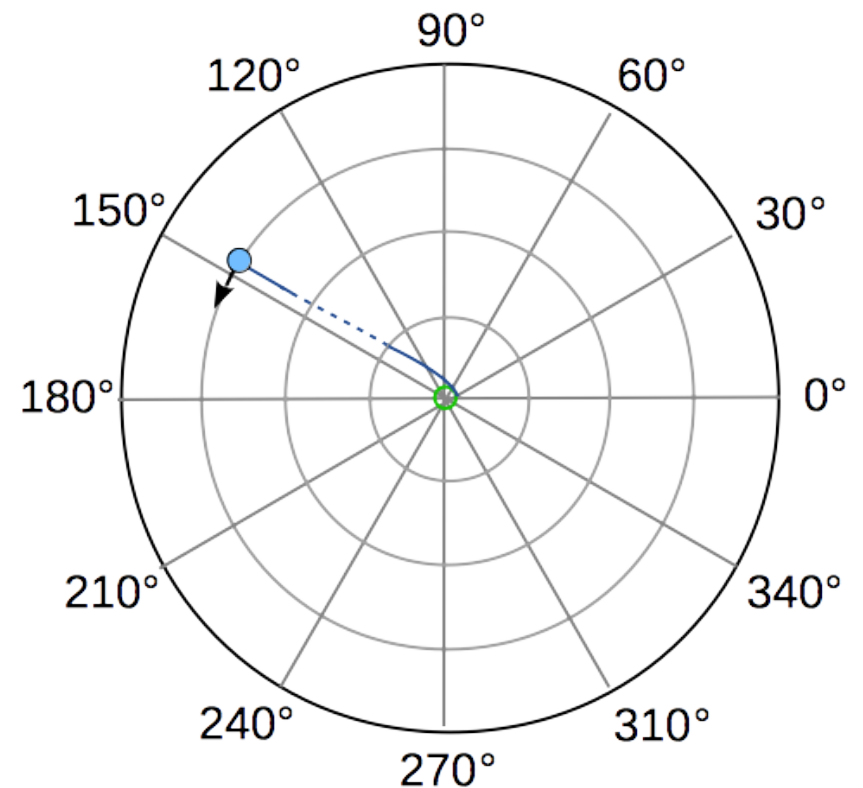
## *Flyout Trajectories & Velocity Profiles*



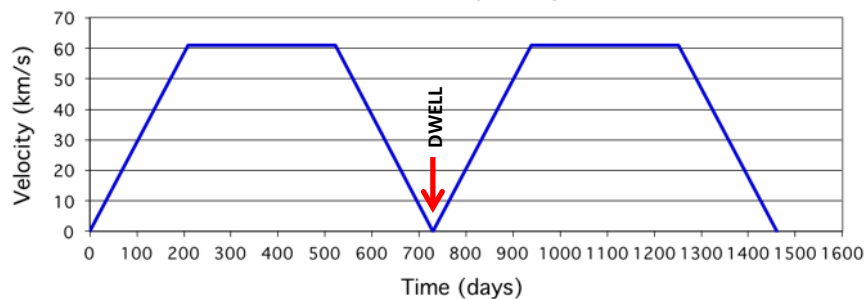
### Uranus Flyout Trajectory



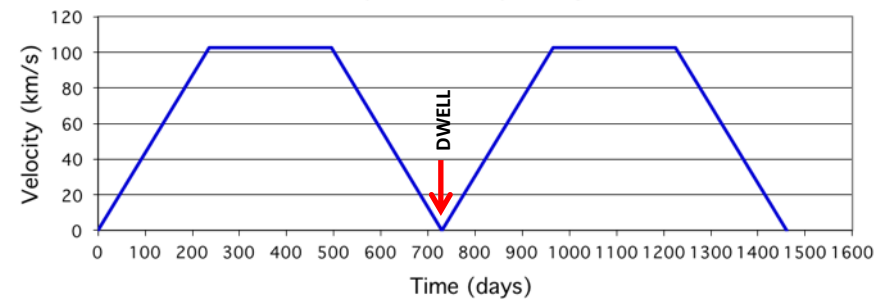
### Neptune Flyout Trajectory



### Uranus Round Trip Velocity Profile



### Neptune Round Trip Velocity Profile







# OUTER PLANET MISSION CASE STUDIES

## *Analysis Summary*



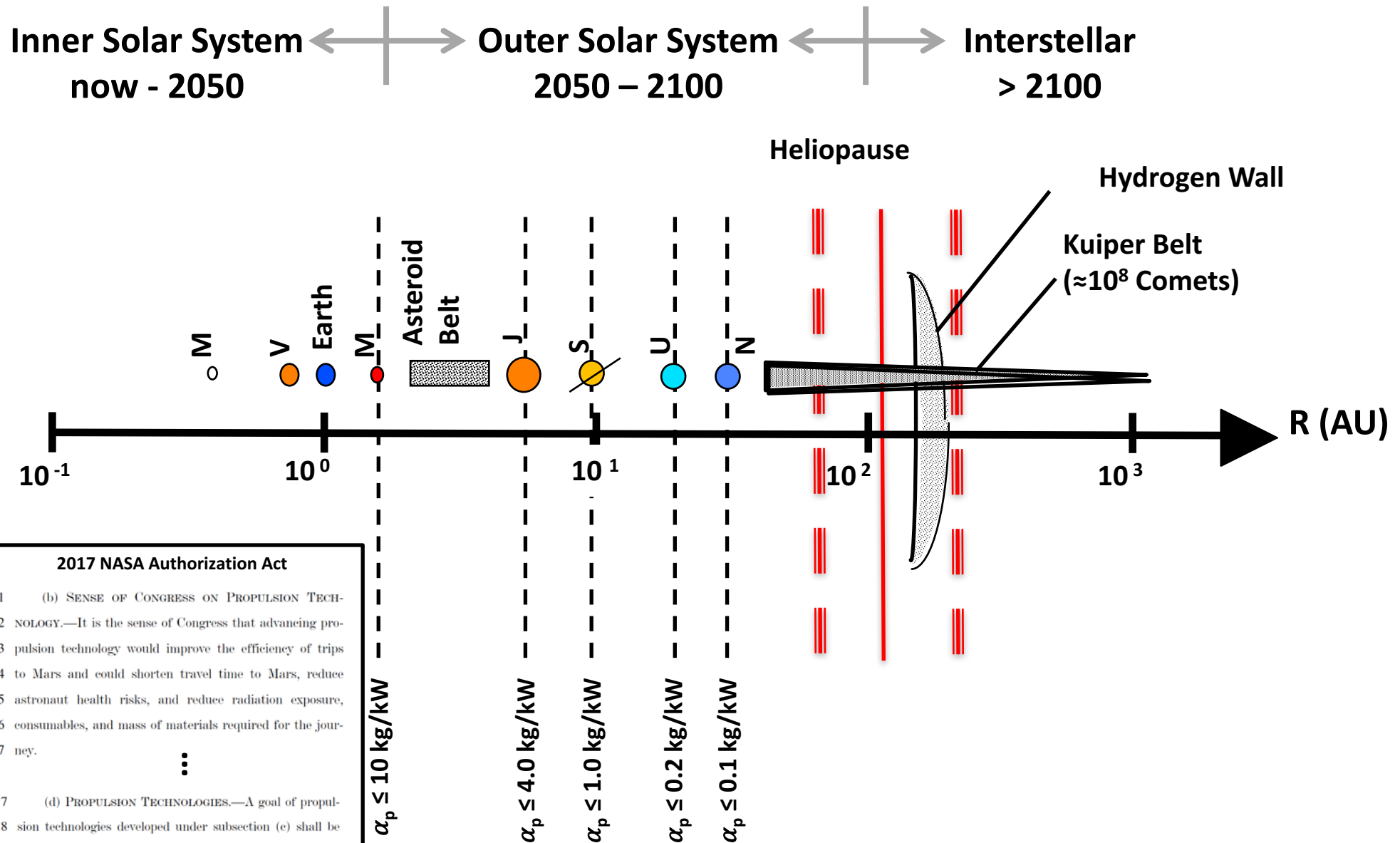
Mission Data	Jupiter	Saturn	Uranus	Neptune
Heliocentric Distance (AU)	5.20	9.50	19.2	30.1
Round Trip Flight Duration (yrs)	4.0	4.0	4.0	4.0
Flyout Time (yrs)	2.0	2.0	2.0	2.0
Flyout Thrust Time (yrs)	1.0	1.2	1.1	1.3
Flyout Payload MF* (%)	20	20	20	20
Propulsion System Power (MW)	100	100	200	200
Thrust Efficiency (%)	80	80	80	80
$C_3$ (km <sup>2</sup> /s <sup>2</sup> )	0	0	0	0
Mission $\Delta V$ (km/s)	27.9	59.2	122.1	205.1
Mission Specific Energy (GJ/kg)	0.365	1.45	8.54	18.3
Thrust (N)	8734	4382	3619	2468
Isp (ksec)	1.87	3.72	9.02	13.22
Launch Mass (Mkg)	19.3	5.9	1.9	1.0
Launch Propellant MF (%)	93	93	93	93
Earth Return Payload MF (%)	2	2	2	2
$\alpha_{\text{propulsion}}$ (kg/kW)	3.47	1.05	0.163	0.090
$\phi_{\text{propulsion}}$ (kW/kg)	0.288	0.952	6.13	11.1

\* Includes habitat, structures, propulsion system, and flyback propellant



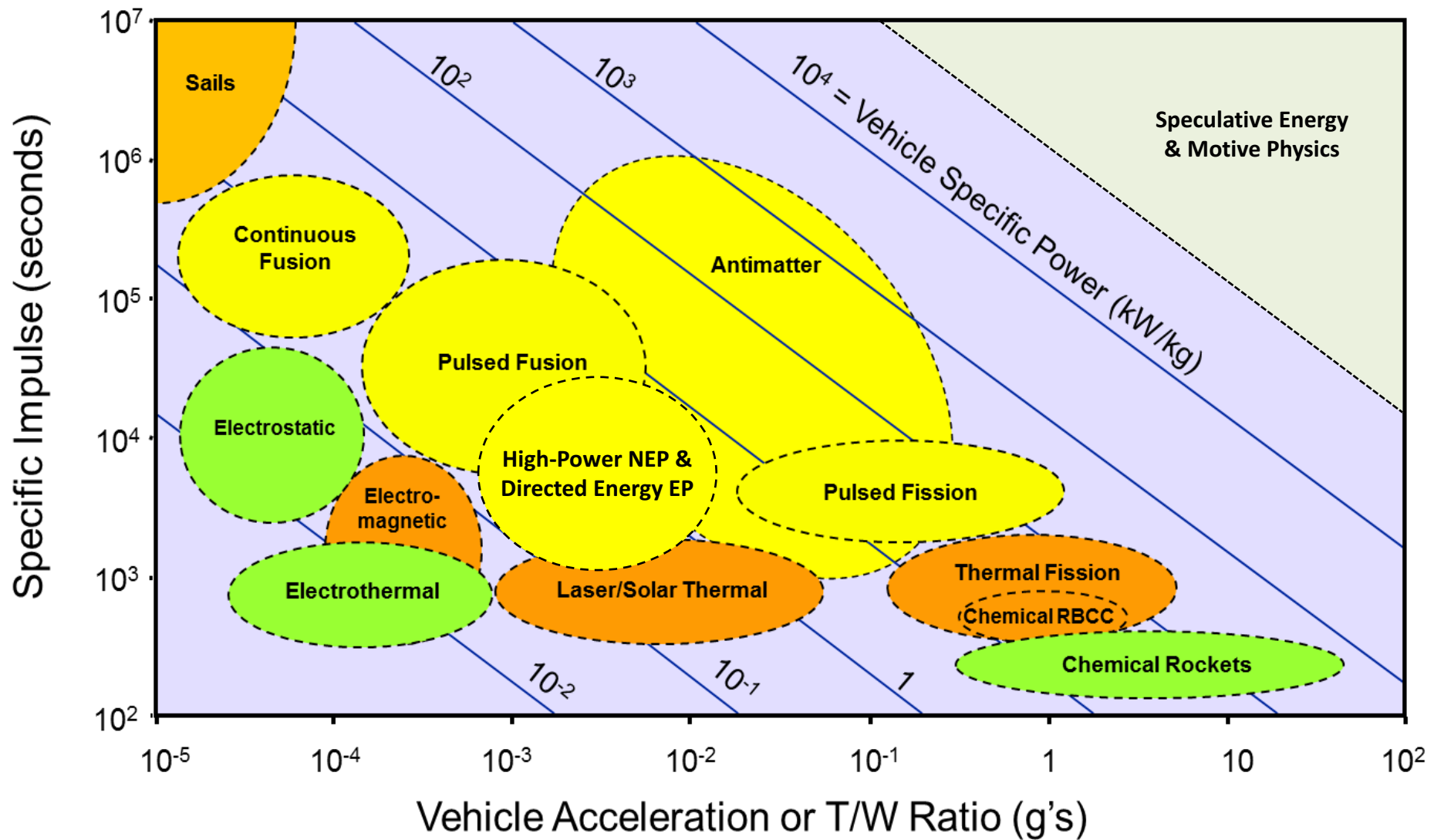
# HSF TRANSPORTATION CAPABILITY NEED

## Propulsion System Specific Mass



# ADVANCED PROPULSION LANDSCAPE

## Technology Capability Regimes



● Unproven Technology (TRL 1-3)    ● Demonstrated Technology (TRL 4-6)    ● Operational Systems (TRL 7-9)



# ADVANCED PROPULSION LANDSCAPE

## Potential Technology Solutions



### Candidate Advanced Propulsion Technology Solutions

#### – Multi-MW-Class NEP

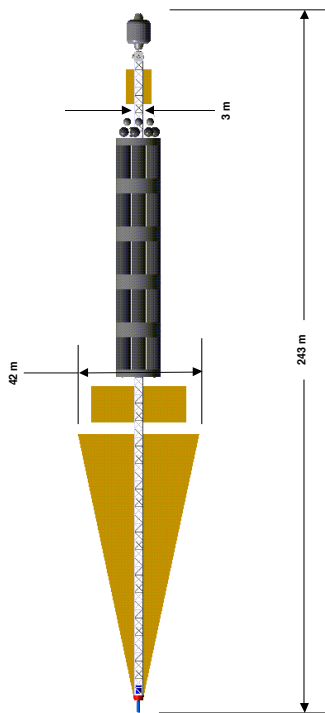
- NTP Derived LEU/CERMET Reactor – De-rate Temperature to 1850 K with High Burn-Up Fuel Design
- He-Xe MHD Brayton Cycle for High-Temperature Heat Rejection & Minimized Radiator Mass
- High-Power EP

#### – Multi-MW-Class Directed Energy EP

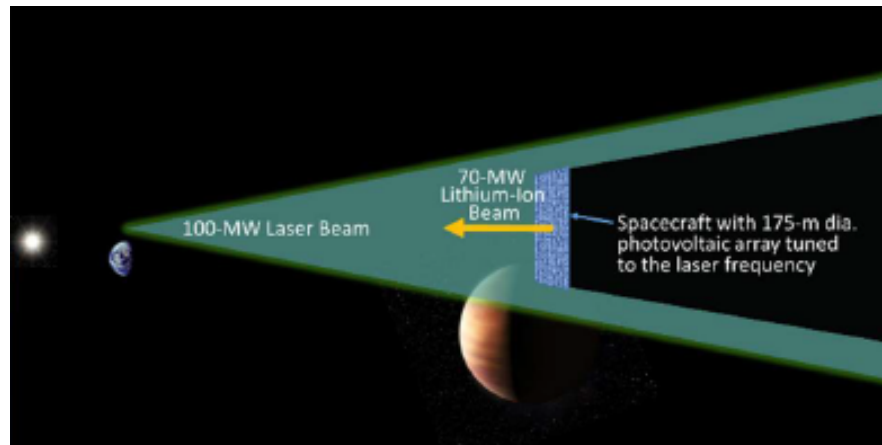
- 100-200 MW Off-Board Laser Array Beaming to 70% Efficient Tuned S/C Photovoltaic Array
- Direct Drive of On-Board High-Thrust, High-Specific-Impulse, Lithium-Fueled Electric Thruster

#### – GW-Class Pulsed Fusion

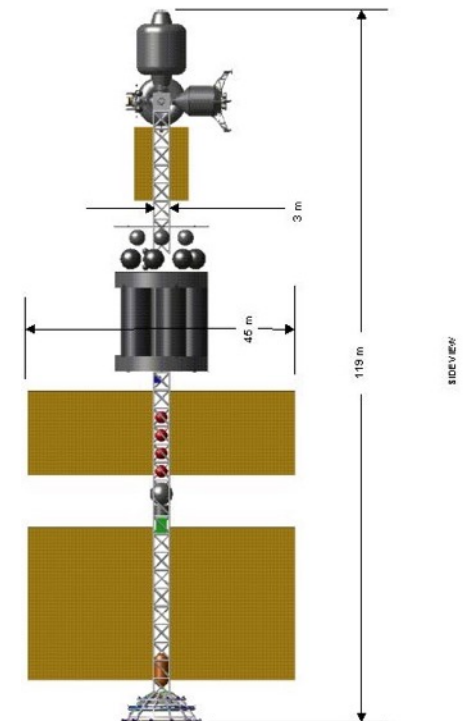
- DT-Driven-DD Pulsed Micro-Fusion in Magnetic Nozzle
- 2-GW Average Jet Power @ 70,000-sec Isp



Multi-MW-Class NEP  
 $\alpha_p = 2\text{-}3 \text{ kg/kW}$   
NETS-2011-3349



Multi-MW-Class Directed Energy EP  
 $\alpha_p = 0.25 \text{ kg/kW}$  (On-Board S/C)  
Privately Communicated JPL Concept



GW-Class Pulsed Fusion  
 $\alpha_p = 0.22 \text{ kg/kW}$   
NASA-TP-2003-212691

# STMD STRATEGIC FRAMEWORK

## Implementation Waterfall



STMD  
Strategic  
Alignment  
Framework

- Core Values
- Guiding Principles
- Implementation Goals Flowdown

STMD  
Strategic  
Themes

- Get There
- Land There
- Live There
- Observe There
- Invest There

STMD  
Transformative  
Themes  
(6)

- Community Oriented Outcomes

STMD  
Thrust  
Areas

- Focused Investment

STMD  
Quantifiable  
Capabilities  
(37)

- Quantified Technical Challenges

Technology  
Portfolio  
Integration

- Crosscutting Strategy
- Content Prioritization

STMD  
Programs

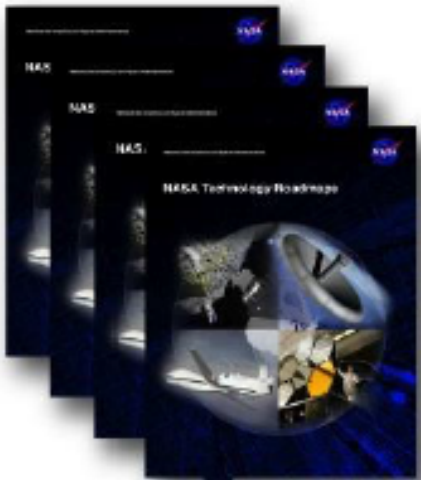
- Implementation

### STMD Transformative Themes

- ❖ *Expand Utilization of Near-Earth Space*
- ❖ *Develop Efficient & Safe Transportation Through Space*
- ❖ *Increase Access to Planetary Surfaces*
- ❖ *Enable Humans to Live & Explore on Planetary Surfaces*
- ❖ *Enable Next Generation of Science Beyond Decadal*
- ❖ *Grow & Utilize the U.S. Industrial and Academic Base*



National Science and Technology Priorities





# **STMD TRANSFORMATIVE THEMES**

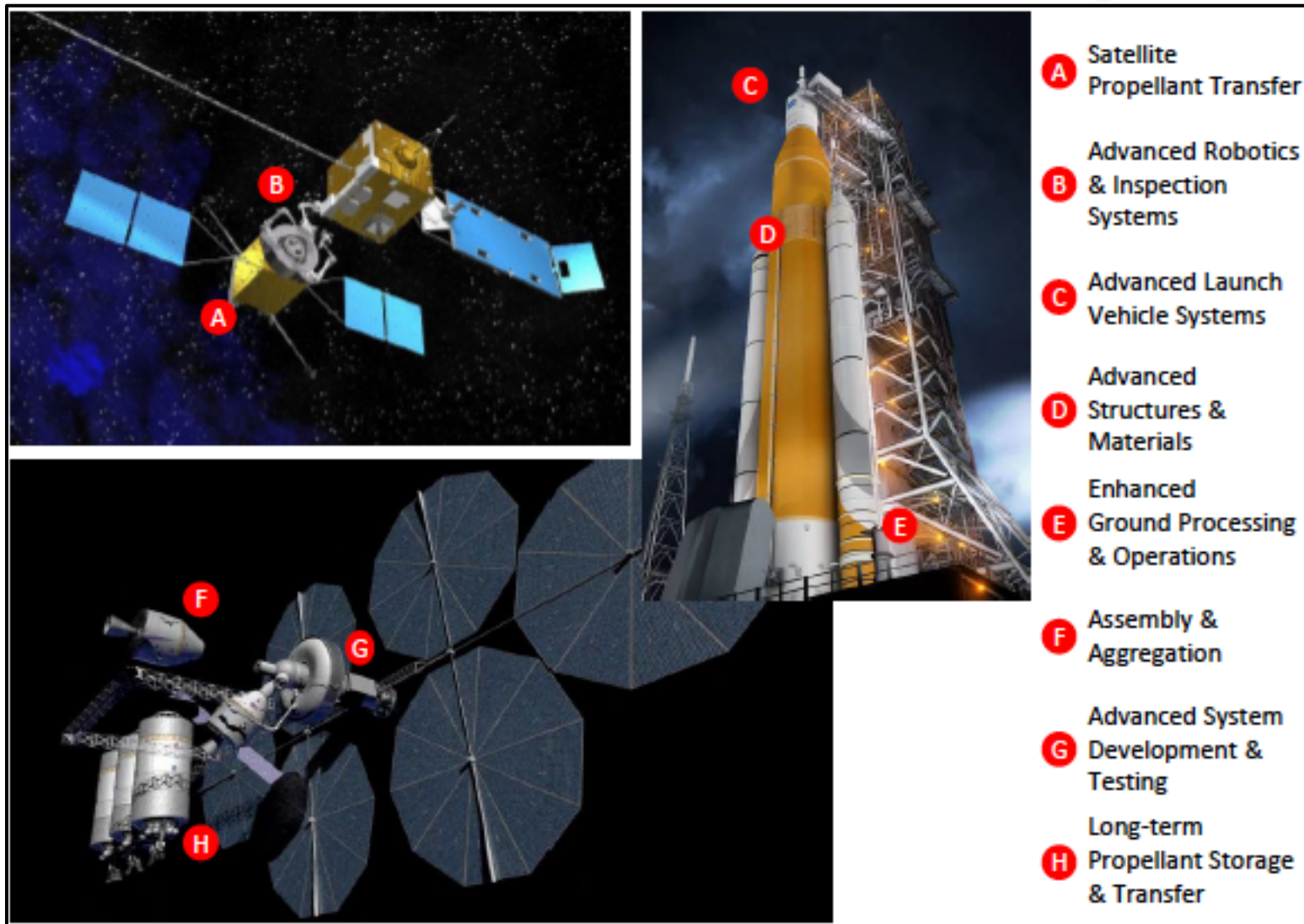
## ***Expand Utilization of Near-Earth Space***



### **THEME-1: EXPAND UTILIZATION OF NEAR-EARTH SPACE**

- Provide Safe & Affordable Routine Access to Space
- Enable Extension, Reuse, and Repair of Near-Earth Assets
- Expand Near-Earth Infrastructure & Services to Support HSF

} **THRUSTS**







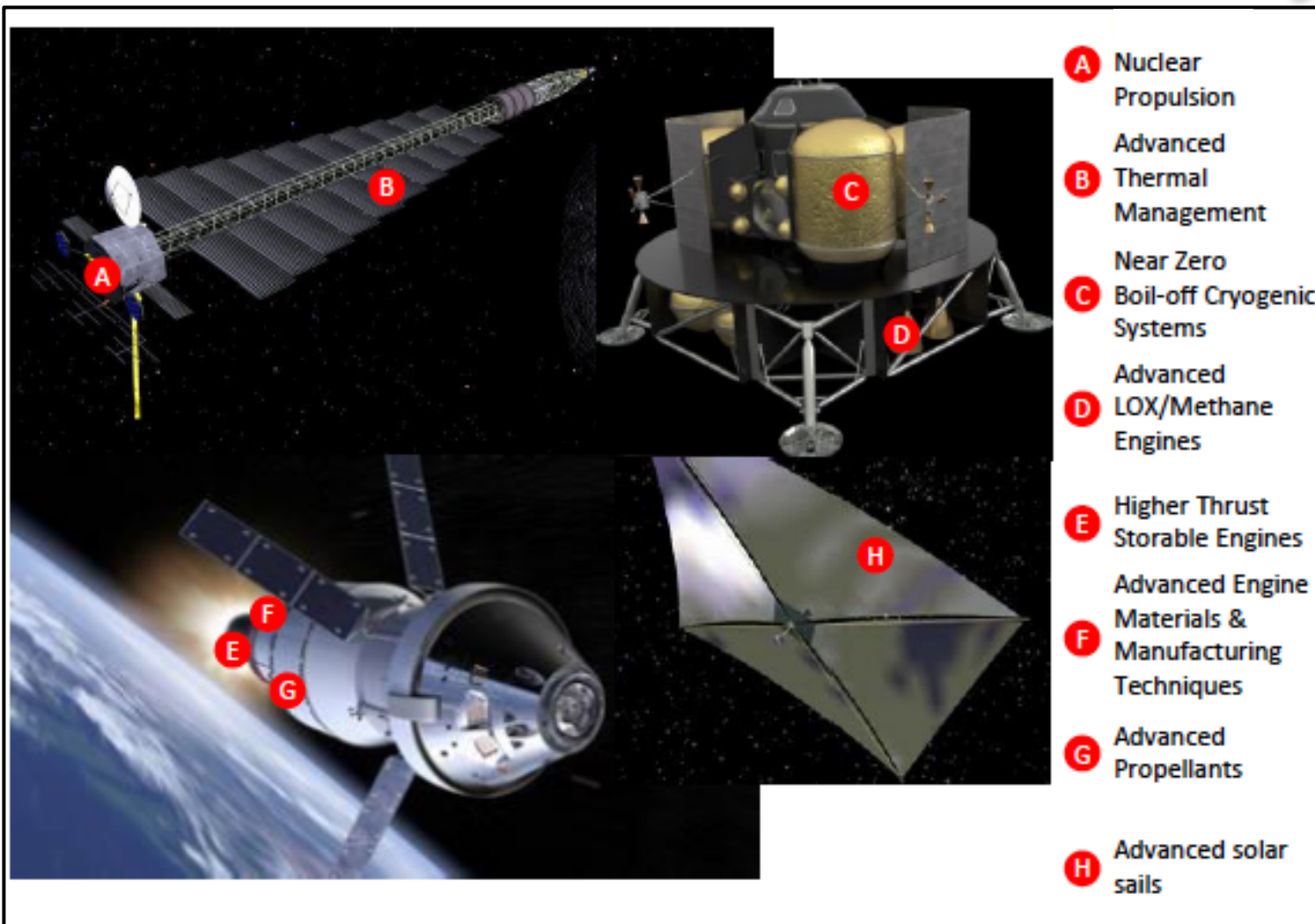
# **STMD TRANSFORMATIVE THEMES**

## ***Develop Efficient & Safe Transportation Through Space***

### **THEME-2: DEVELOP EFFICIENT & SAFE TRANSPORTATION THROUGH SPACE**

- Provide Cost-Efficient, Reliable Propulsion for Long Duration Missions
- Increase Effectiveness & Applicability of Current Propulsion Options
- Enable Faster, More Efficient Deep Space Missions
- Provide Efficient & Safe In-Space Habitation

THRUSTS





# **PROPULSION TECHNOLOGY PRIORITIZATION**

## ***Strategic Recommendations***



<b>Recommended Technology Prioritization</b>	<b>Mission Category</b>
1) Develop and flight demonstrate <b>SEP</b> (12.5 kW HET Quad-Cluster) and establish EMC relevant power extensibility $\geq 150$ kW	Science/Commercial & EMC Hybrid/Split
2) Develop foundational technology for affordable <b>Nuclear Thermal Propulsion</b> and establish viability & feasibility, with good cost & schedule confidence, prior a decision to proceed with full-scale engine system development	EMC NTP & Large Robotics
3) Mature <b>in-space cryogenic liquid engine technologies</b> for the development of integrated MPS/RCS and descent/ascent engines applicable to EMC architecture	EMC Split
4) Develop and demonstrate <b>high thrust, low-freezing-point in-space storable propulsion</b> that reduces spacecraft power burdens and provides for long-duration operation in extreme space environments	Robotic Science & EMC Hybrid
5) Develop and demonstrate <b>small-scale launch systems &amp; <math>\mu</math>-propulsion technologies</b> that would enable affordable high- $\Delta V$ small spacecraft missions	Robotic Space & Commercial
6) Develop and demonstrate <b>green propellant in-space propulsion</b> that simplifies ground launch ops, increases performance, reduces spacecraft burdens, and extends extreme environments operability – facilitate green propellant commercialization & infusion	Robotic Science & Commercial
7) Identify, mature, and execute proof-of-principle demonstrations of <b>breakthrough propulsion technologies</b> that could enable more ambitious missions to Mars & beyond	Large Robotics & Crewed Deep Space



# PROPULSION CAPABILITY OBJECTIVES

## *Quantifiable Capabilities*



Capability Objective	Quantifiable Metrics
High-Power SEP with EMC Extensibility	<ul style="list-style-type: none"> <li>In-Space Demonstration of 12.5-kW Hall Effect Thruster</li> <li>Long Life Thruster enabling Mission Utilization &gt; 1</li> <li>Power Extensibility <math>\geq 150</math>-kW EP</li> </ul>
EMC NTP Propulsion Architecture	<ul style="list-style-type: none"> <li>Thrust <math>\geq 25</math>klbf @ Thrust/Weight <math>\geq 4</math></li> <li>High Temperature Fuel Element Temp <math>\geq 2850</math> K @ Isp <math>\geq 900</math> sec</li> <li><math>\Delta V \geq 10</math> km/s – Enable Opposition &amp; Conjunction EMC Mission Options</li> <li>Fission Product Leakage <math>\ll</math> NERVA/ROVER Milestone</li> <li>Run Duration <math>\geq 2</math> hrs @ rated temperature</li> <li>Engine Restarts <math>\geq 10</math></li> <li>Hydrogen CFM - Zero Boil Off &amp; Liquefaction at Low Power (kW's @ 20k)</li> <li>NTP Engine System Development LCC <math>\approx</math> Comparable Scale LRE LCC (\$1-2B)</li> </ul>
EMC LOX/Methane Propulsion Architecture	<ul style="list-style-type: none"> <li>MPS Thrust <math>\geq 23</math> klbf with 5:1 Throttling Capability</li> <li>RCS Thrust <math>\geq 100</math> lbf with Integrated Feed Systems</li> <li>Isp &gt; 360 sec</li> <li>Lifetime &gt; 300 hours</li> <li>LOX/Methane CFM - Zero Boil Off and Liquefaction at Low Power (100's Watts @ 90K)</li> </ul>
Mission Enhancing In-Space Storable Propulsion	<ul style="list-style-type: none"> <li>100-lbf Class MON-25/MMH Bipropellant Engine (Flight Qualified within 2 years)</li> <li>EMC Scale-Up: RCS Thrust = 100-1000 lbf   MPS Thrust = 25,000 lbf</li> <li>Reduce Propellant Freezing Point &lt; -40 °C</li> <li>Reduce Propulsion System Mass <math>\geq 80\%</math></li> <li>Reduce Propulsion System Volume <math>\geq 50\%</math></li> <li>Reduce Propulsion System Cost <math>\geq 60\%</math></li> </ul>
Enabling Small-Scale Launch & Small Spacecraft Missions	<ul style="list-style-type: none"> <li>5-180 kg payload delivery capacity to 350-700 km (CONUS &amp; Sun Synchronous Ops)</li> <li>Launch Costs &lt; \$60,000/kg; <math>m_p \geq 50</math>kg</li> <li>Launch Costs &lt; \$3M/Launch; <math>m_p &lt; 50</math>kg</li> <li>Small S/C Sub-KW EP: <math>\Delta V &gt; 5</math>km/s @ &lt;1-kW with 7x Increase in Propellant Throughput</li> </ul>
Mission Enhancing In-Space Green Propulsion	<ul style="list-style-type: none"> <li>Scale-Up: 22-N Green Monopropellant Thruster (Flight Qualified within 3-5 years)</li> <li>Scale-Up: 110-N Thruster (5-7 years), 440-N Thruster (7-10 years)</li> <li>Increase Density-Isp <math>\geq 25\%</math></li> <li>Reduce Propellant Freezing Point &lt; -40 °C</li> <li>Reduce Thruster Power Consumption <math>\geq 50\%</math></li> <li>Increase Propellant Throughput/Lifetime <math>\geq 125</math> g</li> <li>Reduce Ground Operation Costs <math>\geq 50\%</math> (Reduce or Eliminate SCAPE Suit Ops)</li> </ul>
Breakthrough In-Space Propulsion	<ul style="list-style-type: none"> <li>Ultra Low Propulsion System Specific Mass: <math>\alpha \leq 5</math>kg/kW</li> </ul>





# CAPABILITY DEVELOPMENT STRATEGY

## *Diversified Propulsion R&T Investments*



### Inner Solar System now – 2050

### Outer Solar System 2050 – 2100

#### IN-SPACE PROPULSION – Near Term Focus ( $3 \leq \text{TRL} \leq 6$ )

Technology investments in key areas enable evolved capability and modest gains in capability – *PROGRESS IS PREDICTABLE*

#### ADV PROPULSION – Far Term Focus ( $\text{TRL} < 3$ )

Sustained research investment enables possibility for new revolutionary technologies – *PROGRESS IS NOT PREDICTABLE*

##### Advanced Chemical Propulsion

###### Key Technologies:

- Advanced Propellants
- Long-term CFM
- ISRU (LOX/Methane)

###### Capability Goals:

- Reduced SWaP
- Low Freezing Point
- Non-Toxic

##### Combined Chemical-Electric Propulsion

##### Solar Electric Propulsion

###### Key Technologies:

- Light Weight Deployable Arrays
- Extreme Environment Arrays
- High-Power/Isp Thrusters

###### Capability Goals:

- Flight Demonstration
- Robust Array Ops
- High Power Scaling

##### Bimodal Nuclear Thermal-Electric Propulsion

##### Nuclear Thermal Propulsion

###### Key Technologies:

- Robust High-Temperature Fuels
- High Power Density LEU Reactor
- Affordable Development & Testing

###### Capability Goals:

- LEU FE Prototype
- NTP Design/Costing
- Affordable Dev/Test

##### Revolutionary Unproven Energetic Propulsion Concepts

*High Power NEP, Advanced Fission, Fusion, etc*

#### Sustained Low-Level Research Investment

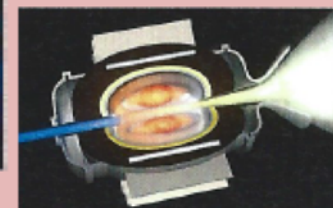
Research on Advanced Energetic Processes & Concepts

*Tangible Action to Remove "Barriers to Innovation"*



Multi-MW NEP

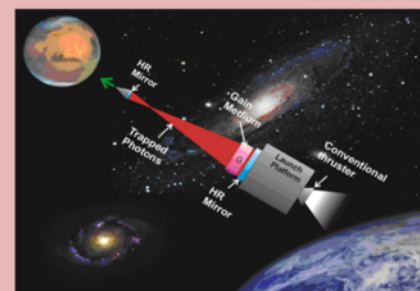
Fast Mars  
Tech Push



Fission Gas Core or  
Enhanced Solid Core



Pulsed Fission



Photonic Laser Thruster



Pulsed Fusion



Antimatter



Breakthrough Science

- Capability Goal:
- $\alpha < 5 \text{ kg/kW}$

